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Cost implications for thermomechanical pulping and brightening of blue-stained chips

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Abstract

Thermomechanical and chemithermomechanical pulps were prepared and tested from blue-stained and sound lodgepole pine samples. Blue-stained samples had higher amounts of fine and pin chip content and slightly less basic chip density than did the sound samples. There was no well-defined relationship between refining energy, fibre properties, strength properties, or optical properties of thermomechanical and chemithermomechanical pulps prepared from blue-stained and sound lodgepole pine chips.

Blue-stained pine thermomechanical pulping responded poorly to sodium hydrosulfite bleaching, but responded to alkaline hydrogen peroxide bleaching as well as the unstained pine thermomechanical pulping did at high peroxide charges. The light stability of the peroxide-bleached, blue-stained thermomechanically pulps was identical to that of the peroxide-bleached, unstained thermomechanical pulps.

Blue-stained pine chemithermomechanical pulps also responded poorly to sodium hydrosulfite bleaching, but responded to alkaline hydrogen peroxide bleaching better than did the unstained pine chemithermomechanical pulps. The light stability of the peroxide-bleached, blue-stained chemithermomechanical pulps was also slightly higher than that of the peroxide-bleached, unstained control.

The hydrosulfite-bleached, blue-stained thermomechanical or chemithermomechanical pulps had the advantage of low yellowness (CIE b*) over the bleached, unstained pulp.

Résumé

On a préparé et mis à l'essai des pâtes thermomécaniques et chimico-thermomécaniques à partir d'échantillons de pins tordus bleuis et en bonne santé. Les échantillons bleuis contenaient plus de copeaux fins et sous-dimensionnés, ainsi que légèrement moins de copeaux basiques que les échantillons sains. Il n'y avait pas de relation bien définie entre l'énergie de raffinage, les propriétés des fibres, les propriétés de résistance ou les propriétés optiques des pâtes thermomécaniques et chimico-thermomécaniques préparées à partir de copeaux de pin tordu sain ou bleui.

La pâte thermomécanique obtenue à partir de pin bleui répondait mal au blanchiment au dithionite de sodium, mais répondait au blanchiment au peroxyde d'hydrogène alcalin aussi bien que la pâte thermomécanique de pin sain à des charges de peroxyde élevées. La stabilité à la lumière des pâtes thermomécaniques obtenues à partir de pin bleui et blanchies au peroxyde était identique à celle des pâtes thermomécaniques obtenues à partir de pin sain et blanchies au peroxyde.

La pâte chimico-thermomécanique obtenue à partir de pin bleui répondait également mal au blanchiment au dithionite de sodium, mais répondait mieux au blanchiment au peroxyde d'hydrogène alcalin que la pâte chimico-thermomécanique de pin sain. La stabilité à la lumière des pâtes chimico-thermomécaniques bleuies et blanchies au peroxyde était également légèrement supérieure à celle des pâtes obtenues à partir de pin sain et blanchies au peroxyde.

Les pâtes chimico-thermomécaniques ou thermomécaniques obtenues à partir de pin bleui et blanchies au dithionite de sodium comportaient l'avantage d'être moins jaunes (CIE b*) que les pâtes blanchies et obtenues à partir de pin sain.

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Introduction

Lodgepole pine (*Pinus contorta* Dougl.) forests make up approximately 35% of British Columbia's forested land base and account for 25% of the province's total volume harvested (Miller et al.1993). Mountain pine beetle (*Dendroctonus ponderosae* Hopk.) is currently B.C.'s most devastating forest insect and it has wrought more destruction in mature lodgepole pine forests than any other forest insect. In an attempt to deal with the pine beetle infestation, an accelerated harvesting of pine stands damaged with this insect has been ordered by B.C. Ministry of Forests throughout the north central part of the province. Mature lodgepole pine trees attacked by the pine beetle are afflicted through the introduction of *Ophiostoma piliferum*, a fungus that causes blue stain in the sapwood. Initial colonization of lodgepole pine sapwood with this fungus generally causes no structural damage or decay. In general, sawmill residual chips for pulp and paper mills are prepared from outer or sapwood as the stem is processed into lumber. Consequently, the percentage of blue stain in sawmill chips from mountain pine beetle-attacked trees will be significant. Interior SPF (white spruce/lodgepole pine/subalpine fir) chips are the most expensive furnish used in many mechanical pulping operations in British Columbia. Mechanical pulps made from SPF are highly prized for its high brightness and excellent pulp strength properties. As the pine content of SPF increases in response to accelerated lodgepole pine harvesting patterns, the blue stain content of the chips will increase, and storage of pine chips will result in the inoculation of previously clean chips with this fungus.

Published literature on thermomechanical (TMP) and chemithermomechanical (CTMP) pulping of mountain pine beetle-killed lodgepole pine is limited (Thomas 1985; Lougheed et al. 2003; Gee at al. 2004). In a thermomechanical pulping study we found that there was no well-defined relationship between energy consumption and length of time since beetle infestation, however, up to 2-year-beetle-infested pine trees can be used without any significant detrimental effects on either mechanical or optical properties of these mechanical pulps. Thomas reported that there were no clear-cut relationships between strength characteristics and length of time since tree death in CTMP pulping of lodgepole pine, however tear index usually decreased with increasing time since beetle attack (Thomas 1985). Blue-stained lodgepole pine chips from beetle-infested trees were found to be a highly acceptable chip furnish for TMP and BCTMP pulping processes (Lougheed et al. 2003). A thermomechanical pulping study of beetle-killed P*inus ponderosa* concluded that dead trees would be suitable for pulp and paper products (Troxel et al. 1980). Woo et al. reported that the beetle-infested pine trees had substantial moisture loss, lower wood density, and significantly lower concentrations of extractives when compared to sound pine trees (Woo et al. 2003).

Very limited data on the bleaching of pulps made from blue-stained logs/chips are available in the literature. Unbleached, Mg-bisulfite pulp made from blue-stained wood was found to be dark and remained much darker than that from sound wood after bleaching with chlorine-based chemicals (Loyttyniemi and Uusvaava 1972). CTMP made from chips containing blue-stained lodgepole pine was reported to have an overall poorer response to sodium hydrosulfite bleaching, but a better response to alkaline hydrogen peroxide bleaching than the control, unstained CTMP (Lougheed et al. 2003). Unfortunately, the species composition of the blue-stained CTMP (96% pine and 4% spruce) was drastically different than that of the control pulp (61% pine, 37% spruce and 2% balsam fir). It was not clear whether the different bleachability of the blue-stained and the unstained CTMP was due to the effect of blue-staining or to the difference in species composition.

Because of the presence of lignin, both unbleached and bleached mechanical pulps have a characteristic yellow color (yellowish tint) as represented by a high CIE yellow coordinate (b*) value. When bleached mechanical pulps are used along with bleached chemical pulps in high-grade papers, a blue dye has to be added to offset the yellow color (to lower the CIE b*) and give the paper a whiter impression.

This preliminary study was undertaken to quantify the costs associated with thermomechanical and chemithermomechanical pulping and brightening the mechanical pulps produced from blue-stained and sound lodgepole pine chips.

Experimental

Sample Selection

Six hundred and twenty four pieces of rough 2"x 4" x 96" lumber was obtained from Riverside Forest Products, Armstrong, B.C. The wood samples were hand sorted into blue-stained and sound.

Chip Preparation and Chip Quality

Representative pieces of blue-stained and sound wood samples were chipped individually using a 36-inch CM&E 10-knife disc chipper. Chips from each sample were well mixed and representative samples taken for TMP and CTMP pulping trials. Each of the two chip samples were screened on a Burnaby Machinery and Mill Equipment Ltd. two-deck laboratory chip classifier to remove oversize (>31 mm) and fine (<8 mm) material and their solids contents determined.

Loose chip packing density was determined by the method described by J.V. Hatton (Hatton 1979). Chip densities were determined by a modified PAPTAC method A.1H. A method developed by Paprican, using Diffuse Reflectance Infrared Fourier Transform Spectroscopy, was performed to determine the degree of decay in the chip samples (Stirling et al. 2003).

Refining

Accept chips from blue-stained and sound samples were used to prepare TMP and CTMP pulps. In first-stage refining a 30.5 cm Sunds Defibrator TMP 300 single-disc laboratory refiner was used incorporating a Labview PC system to control and/or monitor the refining variables. This refiner is equipped with a built-in screw impregnator for treatment of chips with desired chemicals for CTMP pulping process. A 3.5% Na_2SO_3 solution with pH 9.7 was used; this provided a chemical charge of 3.4 and 3.0% Na_2SO_3, OD wood for blue-stained and sound chips, respectively. Other pertinent refining conditions for the first-stage mechanical pulping are shown below.

Plates	: rotor, No. 3809 modified Stator, No. 3804 modified
Preheater pressure	: 152 kPa
Refiner housing pressure	: 186 kPa
Presteaming time	: 10 min (atmospheric pressure)
Residence time	: 10 min
Pulp consistency	: 24 to 27% OD pulp (cylone exit)
Prex compression ratio	: 3:1

A high freeness pulp sample from each of the primary refining trials was given one or more further passes in a 30.5 Sprout Waldron open-discharge laboratory refiner equipped with type D2A507 plates. TMP and CTMP pulps from both blue-stained and sound lodgepole pine chips with the target Canadian Standard Freeness of 100 mL CSF were brightened using alkaline peroxide and hydrosulfite.

After latency removal, each pulp was screened on a 6-cut laboratory flat screen and screen rejects determined. Bauer-McNett fibre classifications were carried out on screened pulps. Fibre length of each of the TMP and CTMP pulps were determined on a Fibre Quality Analyzer (FQA) instrument. Handsheets were prepared with white water recirculation to minimize the loss of fines and tested for bulk, physical, and optical properties using PAPTAC standard methods. Handsheet roughness was measured in Sheffield units (SU).

Chelation of Unstained and Blue-stained Pine TMP or CTMP

Prior to bleaching with sodium hydrosulfite or alkaline hydrogen peroxide, both the control, unstained (sound) pine TMP (or CTMP) and the blue-stained pine TMP (or CTMP) were treated with 0.5% [based on oven-dried (OD) weight of the pulp] of diethylenetriaminepentaaetic acid, pentasodium salt, DTPA-Na_5, at 1.5% consistency (Cs.), pH 5.0 and 50 ^{o}C for 30 minutes to remove transition metal ions from the pulps to give, respectively, the chelated, unstained pine TMP (or CTMP) and the chelated, blue-stained pine TMP (or CTMP).

Bleaching of Unstained and Blue-stained Pine TMP or CTMP with Sodium Hydrosulfite

The chelated, unstained or blue-stained pine TMP or CTMP (8 or 12 g OD) was placed in a polyethylene bag that was then flushed three times with nitrogen, N_2. A pH 6.0 buffer solution (20 mL of 0.1 M potassium dihydrogenphosphate, KH_2PO_4, and 2.24 mL of 0.1 M sodium hydroxide, NaOH, per 4 g OD pulp) was diluted in a beaker with an amount of deionized (DI) H_2O needed to give a 4.0% Cs. pulp when combined with the pulp. The buffer solution was purged with N_2 for 30 minutes before 0.4 – 2.0% (OD pulp) of sodium hydrosulfite, $Na_2S_2O_4$, was added. The mixture was then added to the pulp in the polyethylene bag. The N_2 in the bag was squeezed out and the bag was sealed, and then immersed in a water-bath at 60 °C for 2 hours. At the end of bleaching, the polyethylene bag was cooled in a cold water-bath to room temperature (~ 20 °C). The pulp was diluted with DI H_2O to 0.75% Cs. The pulp slurry was filtered with the filtrate being recycled once to recover the fines. The same dilution and filtration were then repeated once. The filtered pulp was used to make two or three handsheets (200 g/m^2) according to PAPTAC Test Methods, Standard C.5. The %ISO brightness and CIE b* of the sheets were determined in a Technibrite Micro TB-1C instrument according to PAPTAC Test Methods, Standard E.1, and their average values recorded.

Bleaching of Unstained and Blue-stained Pine TMP or CTMP with Alkaline Hydrogen Peroxide

The chelated, unstained or blue-stained pine TMP or CTMP (12 g OD) was mixed in a Hobart mixer with various amounts of hydrogen peroxide, H_2O_2 (0.6 – 6.0% OD pulp), NaOH (0.6 – 6.0% OD pulp), 1.0% (when $H_2O_2 \leq 1.8\%$ OD pulp) or 3.0% (OD pulp) of sodium silicate, Na_2SiO_3, 0.05% (OD pulp) of magnesium sulphate, $MgSO_4$, and DI H_2O to give a 20% Cs. pulp. The pulp was transferred to a polyethylene bag. The bag was sealed and immersed in a hot water-bath at 60 °C for 3 hours with manual mixing every hour. At the end of bleaching, the polyethylene bag was cooled in a cold water-bath to room temperature (~ 20 °C) and a small amount of filtrate (~ 5 mL) was pressed out by hand and analyzed for residual peroxide content according to PAPTAC Test Methods, Standard J.16P. The pulp was diluted with DI H_2O to 0.75% Cs. The pH of the pulp slurry was lowered to 6.5 – 7.0 with 6% aqueous SO_2 solution. The pulp slurry was filtered with the filtrate being recycled once to recover the fines. The same dilution, pH adjustment and filtration were then repeated once. The filtered pulp was used to make three handsheets (200 g/m^2) according to PAPTAC Test Methods, Standard C.5. The %ISO brightness and CIE b* of the sheets were determined in a Technibrite Micro TB-1C instrument according to PAPTAC Test Methods, Standard E.1, and their average values recorded.

Light-induced Yellowing of Unstained and Blue-stained Pine TMP or CTMP

Light-induced yellowing of the sheets made from selected, peroxide-bleached, unstained and blue-stained pine TMP or CTMP was performed by placing the sheet samples on an office desk under normal, full spectrum fluorescent office lights at a distance of about six feet with the lights being on 24 hours a day. The light intensity for such ambient light exposures was 80 ± 2 lumens/ft^2. The light exposure experiment was stopped at different times to allow for the measurement of the %ISO brightness of the sheets in a Technibrite Micro TB-1C instrument according to PAPTAC Test Methods, Standard E.1.

Results and Discussion

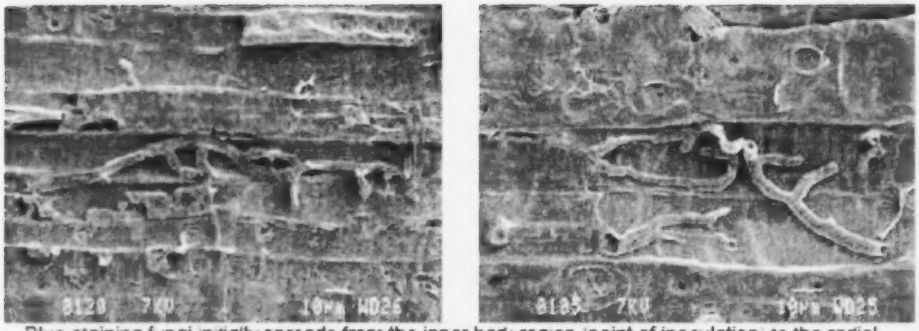
Chip Quality and Classification

The solids contents and chip size distribution of the blue-stained and sound lodgepole pine samples are shown in Table 1. Blue-stained sample had increased fine and pin chip contents than that of sound sample. These results are in agreement with several other investigations which indicated that the quantities of fines and pin chips increased with increasing time since beetle infestation (Lowery et al. 1977; Dobie and Wright 1978; Gee et al. 2004). The caustic solubility (Table 1) results indicate no significant differences between blue-stained and sound samples which suggest that there was no significant amount of decay in the blue-stained chips. Caustic solubility data for both blue-stained and sound samples are within the normal range for sound lodgepole pine. The values of chip density and loose-chip packing density are shown in Table 1. There was no significant difference in loose-chip packing density, however, compared to sound sample the chip density of blue-stained sample was 4%

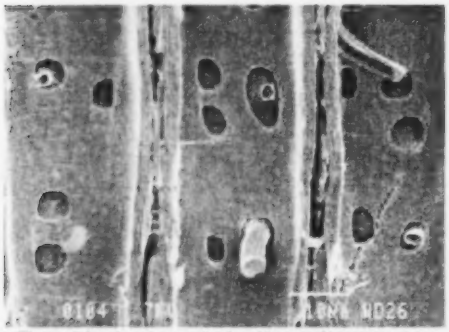
lower. This is in agreement with similar studies of beetle-infested wood showing that chip density will decrease with increasing time since infestation (Ifju et al. 1979; Hitchings and Levi 1981; Hatton 1982). Scanning electron micrographs of blue-stained lodgepole pine wood are shown in Figure 1: Scanning electron micrographs of blue-stained lodgepole pine wood. It shows the spread of fungal hyphae from the inner bark region to the radial parenchyma cells of the sapwood.

Table 1. Sound and Blue-Stained Lodgepole Pine Chip Characteristics.

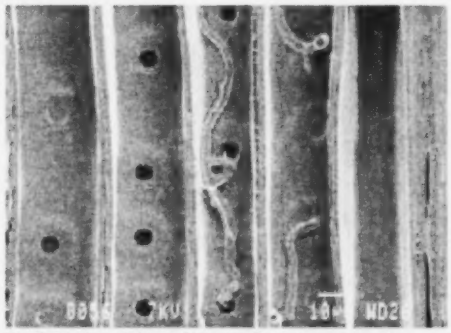
	Sound	Blue Stained
Chip Classification		
45 mm Round Hole (overlarge), %	0.8	1.1
10 mm Slot (overthick), %	7.0	4.7
7 mm Round Hole (accept), %	89.1	89.7
3 mm Round Hole (pins), %	2.5	3.5
Pan (fines), %	0.7	1.1
Chip Density and Solids Content		
Chip Packing Density, kg/m^3	199	193
Chip Basic Density, kg/m^3	405	388
Solids Content, (% wet basis)	90.6	89.1
Chip Caustic Solubility, % (FTIR Method)		
45 mm Round Hole	15.8	19.3
10 mm Slot	22.3	20.5
7 mm Round Hole	15.0	14.0
3 mm Round Hole	16.5	15.1
Pan	21.3	19.2



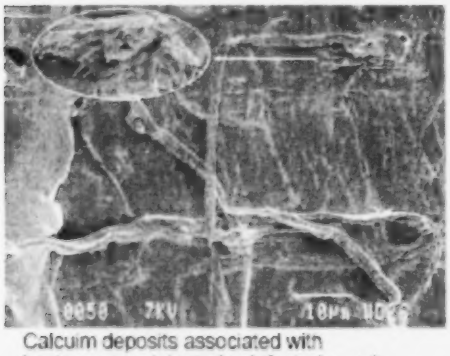
Blue-staining fungi initially spreads from the inner bark region (point of inoculation) to the radial parenchyma tissue of the sapwood.

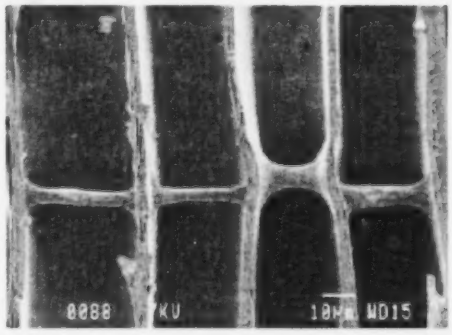


Fungal hyphae penetrate pit membranes to enter the longitudinal tracheids (fibres).



Hyphae travel from fibre to fibre through pit openings in the cell wall.





Calcium deposits associated with hyphae were detected in infested wood.

Figure 1. Scanning electron micrographs of blue-stained lodgepole pine wood show the spread of fungal hyphae from the inner bark to the radial parenchyma cells of the sapwood.

Thermomechanical and Chemithermomechanical Pulping

Raw data for the TMP and CTMP pulp processing, fibre, and handsheet properties of blue-stained and sound lodgepole pine are shown in Appendices A and B, respectively. To facilitate data analysis and discussion, these raw data were standardized by interpolation and extrapolation to a freeness of 100 mL CSF and are shown in Table 2. Similar standardization to a specific energy of 10.0 MJ/kg is also shown in Table 3 to assist the reader and will not be discussed further.

Table 2. Properties of Thermomechanical and Chemithermomechanical Pulps of Sound and Blue Stained Lodgepole Pine Standardized to a Freeness of 100 mL CSF.

Process	Wood Type	Specific Refining Energy (MJ/kg)	R - 48 Fraction (%)	Fines (P-200) (%)	Length Weighted Fibre Length (mm)	Apparent Sheet Density (kg/m^3)	Tensile Index (N•m/g)	Tear Index ($mN•m^2/g$)	Sheffield Roughness (SU)	Scattering Coefficient (cm^2/g)	ISO Opacity (%)	Brightness (%)
TMP	Sound	11.3	52.7	25.4	1.29	338	31	6.4	216	622	96.9	54.7
TMP	Blue-Stained	11.6	54.3	25.8	1.45	340	33	7.0	221	591	96.7	55.2
CTMP	Sound	13.4	54.9	23.0	1.37	379	40	6.9	160	522	95.4	53.9
CTMP	Blue-Stained	12.3	50.9	23.0	1.29	386	39	6.8	148	513	95.6	54.8

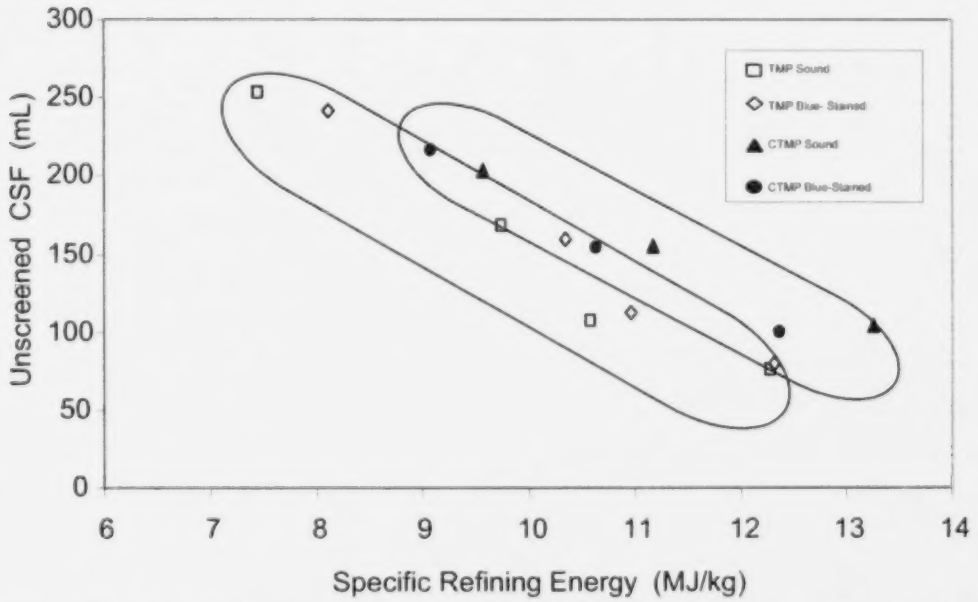


Figure 2. For a given mechanical pulping process, either TMP or CTMP, blue stain had no effect on specific refining energy. However, CTMP pulps from both blue-stained and sound samples required significantly higher refining energy to reach a given freeness than its TMP counterparts.

Table 3. Properties of Thermomechanical and Chemithermomechanical Pulps of Sound and Blue Stained Lodgepole Pine Standardized to a Specific Energy of 10.0 MJ/kg.

Process	Wood Type	Screened CSF (mL)	Length Weighted Fibre Length (mm)	Apparent Sheet Density (kg/m^3)	Tensile Index (N•m/g)	Tear Index ($mN•m^2/g$)	Sheffield Roughness (SU)	Scattering Coefficient (cm^2/g)
TMP	Sound	153	1.41	301	28	7.0	269	590
TMP	Blue-Stained	171	1.63	300	29	8.3	263	554
CTMP	Sound	198	1.48	327	33	8.0	248	494
CTMP	Blue-Stained	173	1.36	341	32	7.2	217	479

Energy Consumption

The specific refining energy consumed to reach a given freeness in the range from 76 to 253 mL CSF is shown in Figure 2: Unscreened Canadian Standard Freeness versus specific refining energy for TMP and CTMP processing. The corresponding values standardized to 100 mL CSF are shown in Table 2. The raw data in Figure 2 and Table 2 also indicate that energy requirements to a given freeness in CTMP processing of blue-stained and sound samples were 6% to 19% higher than those for TMP processing of the same lodgepole pine samples. In general, energy consumption to a given freeness for CTMP increases with increasing chemical uptake by the chips compared to the TMP process (Leask 1987). However, for a given mechanical pulping process, either TMP or CTMP, blue-stained chips had no significant effect on specific refining energy (Figure 2 and Table 2). This confirms our earlier results that up to 3-year-beetle-infested lodgepole pine trees show no significant relationship between energy consumption and length of time since beetle-infestation (Gee et al. 2004).

Since the effects of blue-stain of lodgepole pine chips on energy consumption in TMP and CTMP pulping processes are not clear-cut, more work is required with a large number of samples where length of beetle-infestation and rate of deterioration after beetle-infestation are well-documented.

Fibre Properities

The long-fibre fraction (R-48 fraction), length weighted average fibre length, and fines fraction (P-200) values at a given freeness of 100 mL CSF were not affected by the blue-stain of lodgepole pine trees killed by mountain pine beetle (Table 2). These data would suggest that TMP or CTMP pulps produced from blue-stained lodgepole pine samples should have similar handsheet strength properties to those from sound lodgepole pine samples.

Sheet Consolidation and Strength Properties

At a given freeness of 100 mL CSF, TMP pulps from both blue-stained and sound lodgepole pine samples had lower sheet densities than its CTMP counterparts (Table 2 and Figure 3: Apparent sheet density versus screened Canadian Standard Freeness for TMP and CTMP processing). The standardized data in Table 2 and Figure 3 also show that for a given pulping process, either TMP or CTMP, blue-stain had no effect on sheet density. This confirms our earlier study that up to 3-year-beetle-infested pine trees had no effect on sheet density of TMP pulps (Gee et al. 2004).

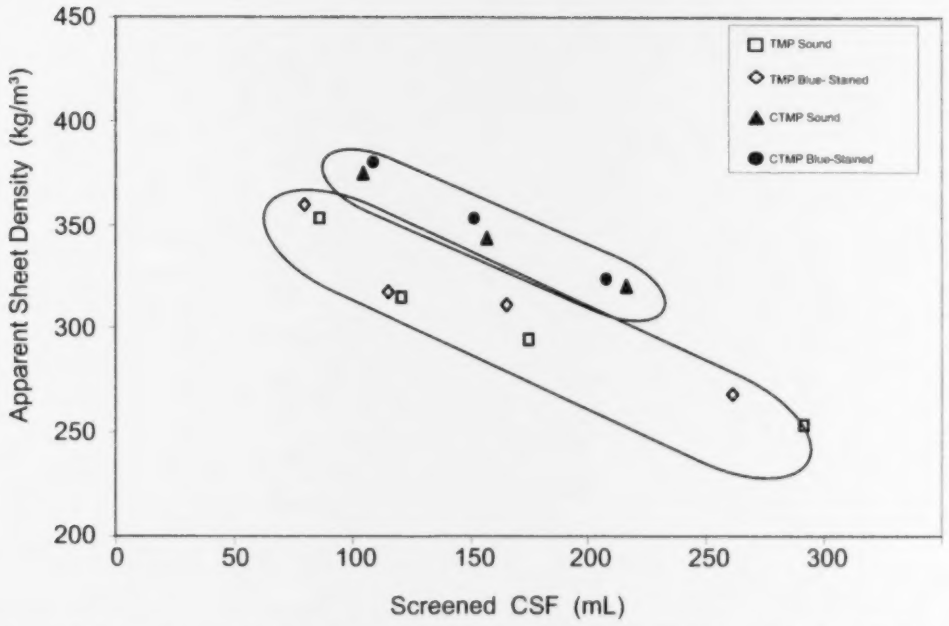


Figure 3. For a given mechanical pulping process, either TMP or CTMP, blue stain had no effect on sheet density. However, TMP pulps from both blue-stained and sound chips had significantly lower sheet densities than its CTMP counterparts.

Tensile index increased with decreasing freeness (Figure 4: Tensile index and screened Canadian Standard Freeness for TMP and CTMP processing), and was consistently larger for CTMP pulps compared with TMP pulps whether pulp are made from blue-stained or sound pine chips. However, standardized data in Table 2 and Figure 4 also show that for a given pulping process, either TMP or CTMP, blue-stain had no effect on tensile strength. This is in agreement with our previous work that up to 2-year-beetle-infested lodgepole pine trees can be used in thermomechanical pulping process without any significant detrimental effects on strength properties (Gee et al. 2004).

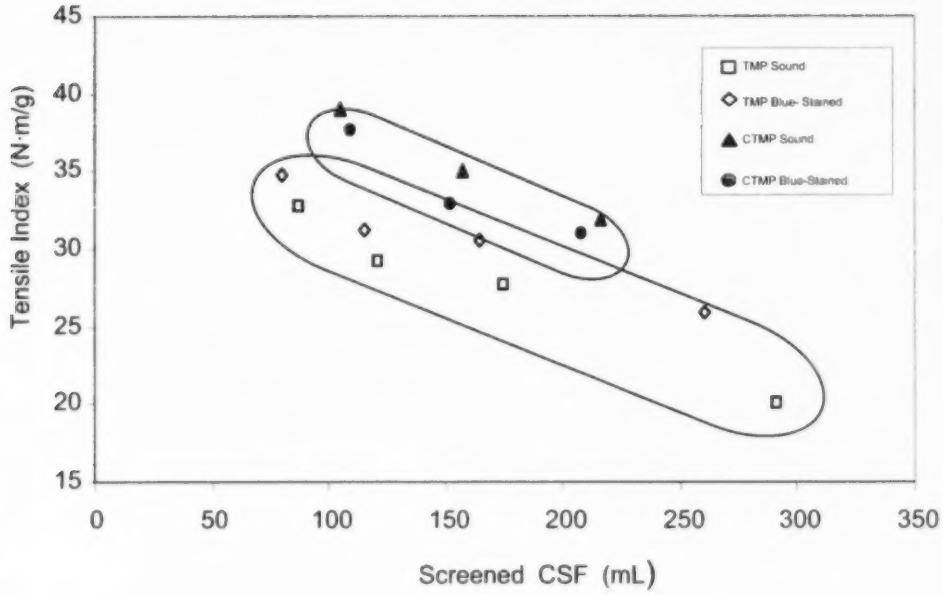


Figure 4. For a given mechanical pulping process, either TMP or CTMP, tensile indices of both blue-stained and sound samples were similar. However, tensile index of CTMP pulps was significantly higher than TMP pulps whether pulps were made from either blue-stained or sound pine chips.

Optical Properties

At a given freeness, blue-stained lodgepole pine sample had slightly lower scattering coefficient values than those from sound sample when the comparison was made on either TMP or CTMP pulping process (Table 2 and Figure 5: Scattering coefficient versus screened Canadian Standard Freeness for TMP and CTMP processing). However, CTMP pulping gave pulps with lower scattering coefficient than TMP pulping from the same pine sample (Figure 5). Blue-stained and sound lodgepole pine pulps had similar sheet roughness properties when the comparison was made on either TMP or CTMP pulping process (Table 2 and Figure 6: Sheffield Roughness versus screened Canadian Standard Freeness for TMP and CTMP processing). However, CTMP pulps were smoother than TMP pulps produced from the same pine sample. Surprisingly, given the presence of blue staining fungi, the brightness values of blue-stained and sound pine samples were identical. This is in agreement with our earlier results where the brightness values of TMP pulps from current, 1-year-, and 2-year-beetle-infested pine trees were similar (Gee et al. 2004). However, the brightness values of TMP pulps from 3-year-beetle-infested pine trees were significantly lower.

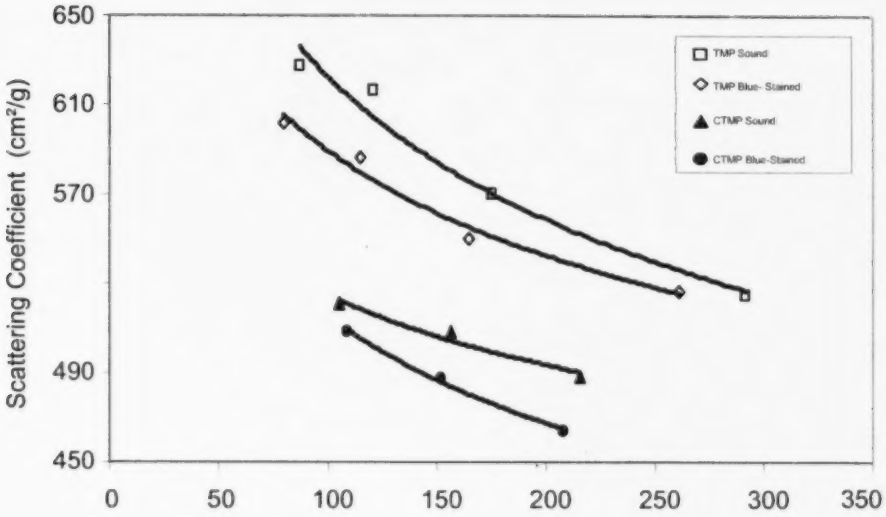


Figure 5. At a given freeness blue-stained pine samples had lower scattering coefficient than those from sound pine samples for both TMP and CTMP pulping processes.

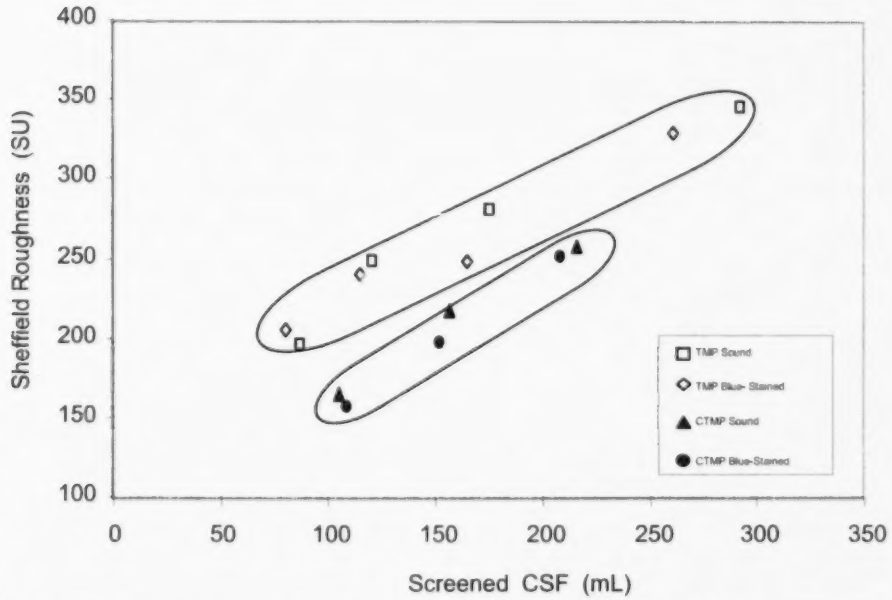


Figure 6. At a given freeness CTMP pulps from both blue-stained and sound pine samples had smoother surfaces than TMP pulps.

Sodium Hydrosulfite Bleaching of Unstained and Blue-stained Pine TMP

The chelated, freshly-prepared blue-stained TMP had an initial brightness of 54.9% ISO, very close to that of the control, unstained TMP (55.2% ISO). However, it did not respond to sodium hydrosulfite bleaching as well as the unstained pulp (Table 4 and Figure 7a Brightness of the unstained and the blue-stained TMP versus charge of sodium hydrosulfite, Na2S2O4). To achieve the same brightness value, a higher charge of sodium hydrosulfite was required for the blue-stained TMP. For example, the blue-stained pulp required more than 1.0% (OD pulp) of Na2S2O4 to obtain a brightness of ~ 61% ISO, while the unstained pulp needed only ~ 0.5% (OD pulp) of Na2S2O4. In addition, the highest achievable brightness for the blue-stained pulp using sodium hydrosulfite at a bleaching temperature of 60 oC was ~ 61.5% ISO, compared to 63.0% ISO for the unstained pulp.

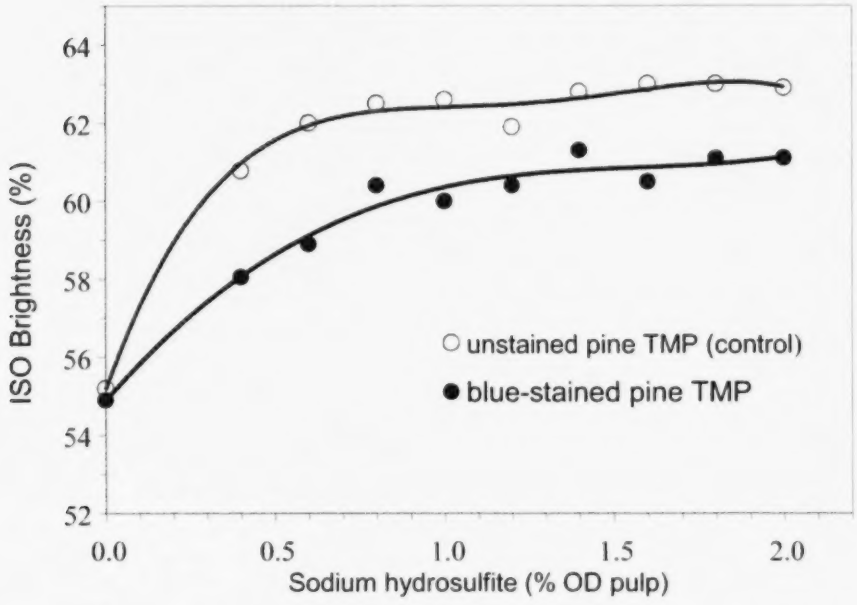


Figure 7a. Brightness of the unstained and the blue-stained TMP versus charge of sodium hydrosulfite, $Na_2S_2O_4$.

The unbleached, blue-stained pine TMP had a lower CIE b* value than the unbleached, unstained pine TMP (Table 4), indicating that it contained the blue-stain. Interestingly, the hydrosulfite-bleached, blue-stained pulps also had lower CIE b* values than the unstained pulps bleached to the same brightness level (Table 4 and Figure 7b: CIE b* versus ISO brightness of the unstained and the blue-stained TMP during sodium hydrosulfite bleaching). This suggested that most of the blue-stain, if not all, remained with the blue-stained pulp after hydrosulfite bleaching.

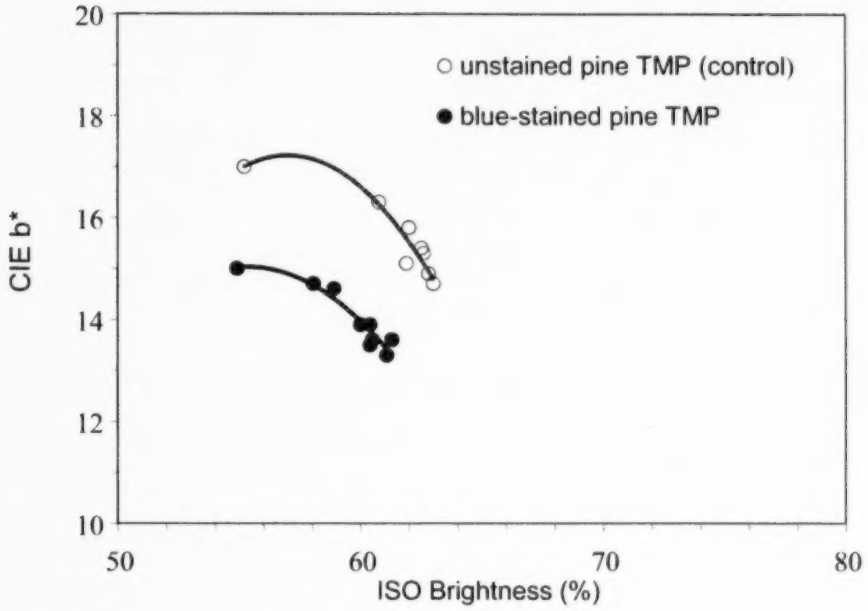


Figure 7b. CIE b* versus ISO brightness of the unstained and the blue-stained TMP during sodium hydrosulfite bleaching.

The poorer bleach response of the blue-stained pine TMP means a higher hydrosulfite bleaching cost, but the lower CIE b* of the bleached pulp may provide some downstream saving on blue-dyes.

Table 4. ISO brightness and CIE b* of the sound and the blue-stained TMP bleached with various amounts of $Na_2S_2O_4$

$Na_2S_2O_4$ (% OD pulp)	Sound TMP		Blue-stained TMP	
	ISO Brightness (%)	CIE b*	ISO Brightness (%)	CIE b*
-	55.2[a]	17.0[a]	54.9[a]	15.0[a]
0.4	60.8	16.3	58.1	14.7
0.6	62.0	15.8	58.9	14.6
0.8	62.5	15.4	60.4	13.9
1.0	62.6 / 62.2[b]	15.3 / 15.2[b]	60.0 / 60.0[b]	13.9 / 14.0[b]
1.2	61.9	15.1	60.4	13.5
1.4	62.8	14.9	61.3	13.6
1.6	63.0	14.7	60.5	13.6
1.8	63.0	14.7	61.1	13.3
2.0	62.9[c]	N/A	61.1[c]	N/A

[a]value for unbleached pulp; [b]duplicate bleaching run; [c]bleaching done on 4 g OD pulp.

Alkaline Hydrogen Peroxide Bleaching of Unstained and Blue-stained Pine TMP

The chelated, freshly-prepared blue-stained TMP did not appear to respond to alkaline hydrogen peroxide bleaching as well as the unstained TMP at low peroxide charges [e.g., < 2.0% (OD pulp) of H_2O_2] (Table 5 and Figure 8a: Brightness of the unstained and the blue-stained TMP versus H_2O_2 charge). The brightness of the blue-stained pulp bleached with 0.6 - 1.8% (OD pulp) of H_2O_2 was 1.0 – 2.0 ISO points lower than that of the unstained pulp. However, at higher peroxide charges [≥ 4.0% (OD pulp) of H_2O_2], the blue-stained TMP responded to alkaline hydrogen peroxide bleaching as well as the unstained TMP; the brightness values of the two bleached pulps were essentially identical.

Interestingly, the difference in the CIE b* between the peroxide-bleached, blue-stained TMP and the peroxide-bleached, unstained TMP became progressively smaller as the charge of peroxide, and consequently the bleached brightness, was increased (Table 5 and Figure 8b: CIE b* versus ISO brightness of the unstained and the blue-stained TMP during alkaline hydrogen peroxide bleaching). This indicated that more and more blue-stain was dissolved/removed from the blue-stained pulp as the charge of alkaline hydrogen peroxide was increased. It is possible that the high concentration of caustic at high alkaline peroxide charge facilitated the dissolution and removal of acids such as 2,3-dihydroxybenzoic acids and ceratenolone. These acids, in the form of their ferric chelates, are thought to be responsible for the blue-stain (Ayer et al. 1986; Ayer et al. 1987).

Table 5. ISO brightness and CIE b* of the sound and the blue-stained pine TMP bleached with various amounts of H_2O_2 and NaOH (see Material and Methods for charges of Na_2SiO_3 and $MgSO_4$)

H_2O_2 / NaOH (% OD pulp)	Sound TMP		Blue-stained TMP	
	ISO Brightness (%)	CIE b*	ISO Brightness (%)	CIE b*
- / -	55.2[a]	17.0[a]	54.9[a]	15.0[a]
0.6 / 0.6	58.0	16.6	57.1	14.7
0.8 / 0.8	59.4	16.5	57.7	14.7
1.0 / 1.0	60.1[b]	16.6[b]	58.8[b]	14.7[b]
1.4 / 1.4	62.6	16.1	60.6	14.3
1.8 / 1.8	63.4[b]	16.0[a]	62.2[b]	14.3[b]
4.0 / 4.0	69.6[c]	13.9[c]	69.6[c]	13.0[c]
5.0 / 5.0	71.9[c]	12.9[c]	71.7[c]	12.4[c]
6.0 / 6.0	72.7[c]	12.5[c]	72.6[c]	12.0[c]

[a]value for unbleached pulp; [b]average of two bleaching runs; [c]average of three bleaching runs.

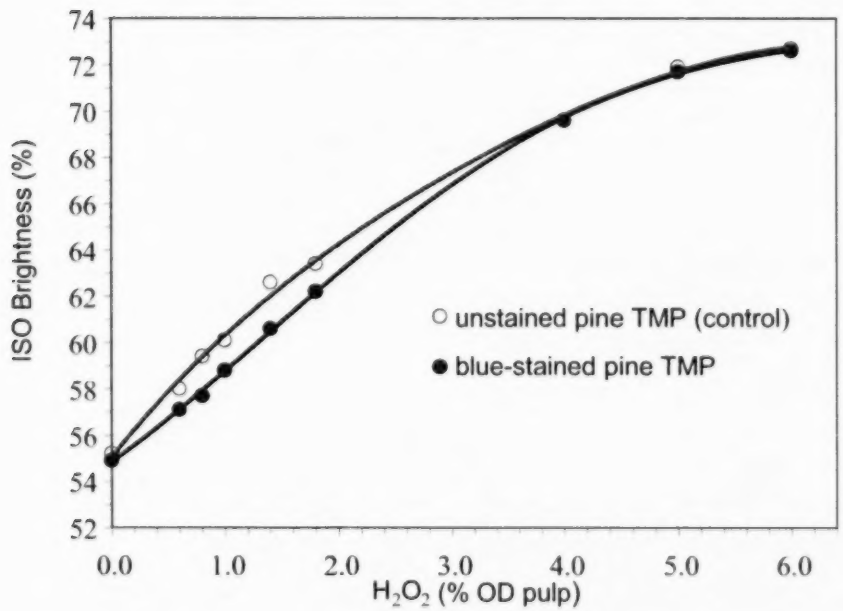


Figure 8a. Brightness of the unstained and the blue-stained TMP versus H_2O_2 charge; NaOH charge = H_2O_2 charge (*see* Material and Methods for charges of Na_2SiO_3 and $MgSO_4$).

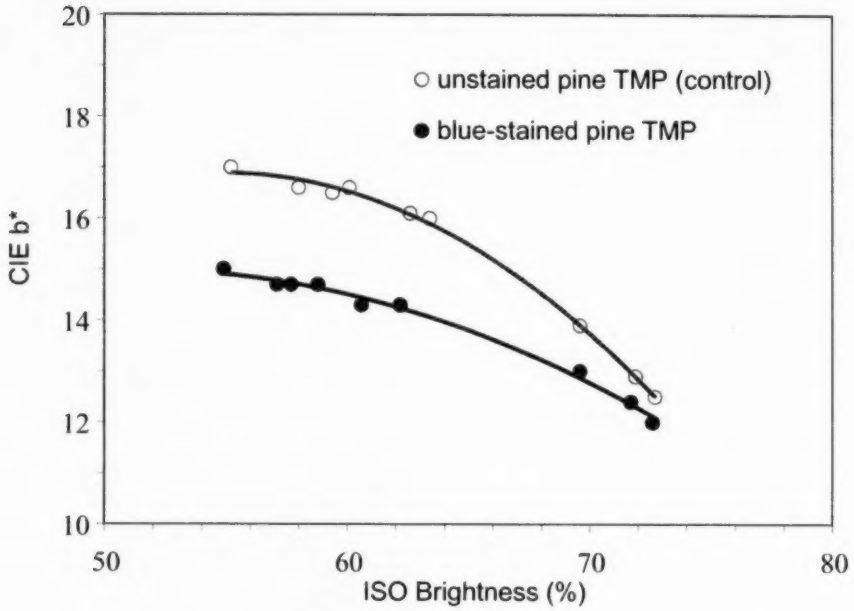


Figure 8b. CIE b* versus ISO brightness of the unstained and the blue-stained TMP during alkaline hydrogen peroxide bleaching.

No significant difference in peroxide consumptions during the bleaching of the blue-stained and the unstained pulps was found (Table 6). At high hydrogen peroxide charges (> 5.0% OD pulp), the effect of caustic was found to be minimal at its optimal charge of 4.0% - 6.0% (OD pulp) (Figure 9: Effect of NaOH on the alkaline hydrogen peroxide bleaching of the unstained and the blue-stained TMP).

The above bleaching data suggest that blue-stained pine TMP is more suitable for the production of peroxide-bleached pulp with > ~ 70% ISO brightness (using > 4.0 H2O2) than for the production of hydrosulfite-bleached pulp with 58% – 62% ISO brightness, in terms of bleaching chemical cost and achievable brightness.

Table 6. Peroxide consumption during the bleaching of the sound and the blue-stained TMP with various amounts of H_2O_2 and NaOH (see Material and Methods for charges of Na_2SiO_3 and $MgSO_4$)

H_2O_2 / NaOH (% OD pulp)	Peroxide consumed (% peroxide applied), sound TMP	Peroxide consumed (% peroxide applied), blue-stained TMP
0.6 / 0.6	83	79
0.8 / 0.8	78	76
1.0 / 1.0	79[a]	77[a]
1.4 / 1.4	77	75
1.8 / 1.8	76[a]	74[a]
4.0 / 4.0	72[b]	71[b]
5.0 / 5.0	70[b]	68[b]
6.0 / 6.0	65[b]	65[b]

[a]average of two bleaching runs; [b]average of three bleaching runs.

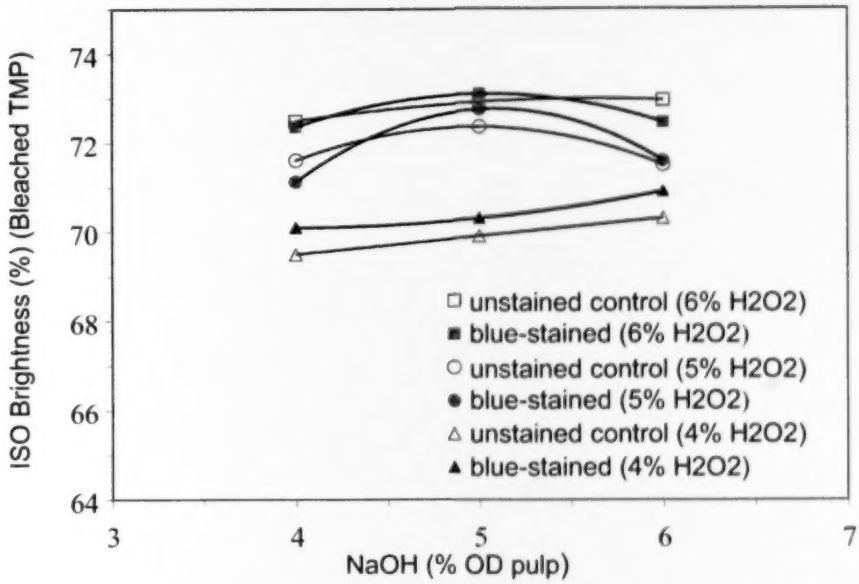


Figure 9. Effect of NaOH on the alkaline hydrogen peroxide bleaching of the unstained and the blue-stained TMP; Na_2SiO_3 = 3.0% (OD pulp) and $MgSO_4$ = 0.05% (OD pulp).

Response of Blue-stained Pine CTMP to Sodium Hydrosulfite and to Alkaline Hydrogen Peroxide Bleaching

The blue-stained pine CTMP had a better response to alkaline hydrogen peroxide bleaching than the unstained pine CTMP, particularly at hydrogen peroxide charges of > 4.0% (OD pulp) (Table 7 and Figure 10a: Brightness of the unstained and blue-stained CTMP versus H2O2 charge). At such charges, the brightness of the bleached, blue-stained pulp was ~ 2.0 – 3.0 ISO points higher than that of the bleached, unstained pulp. To achieve the same brightness value, less bleaching chemicals were needed for the blue-stained pulp than for the unstained pulp. For example, to achieve a brightness of 71.4% ISO, the blue-stained CTMP required only 4.0% (OD pulp) of H2O2, compared to 6.0% for the unstained CTMP.

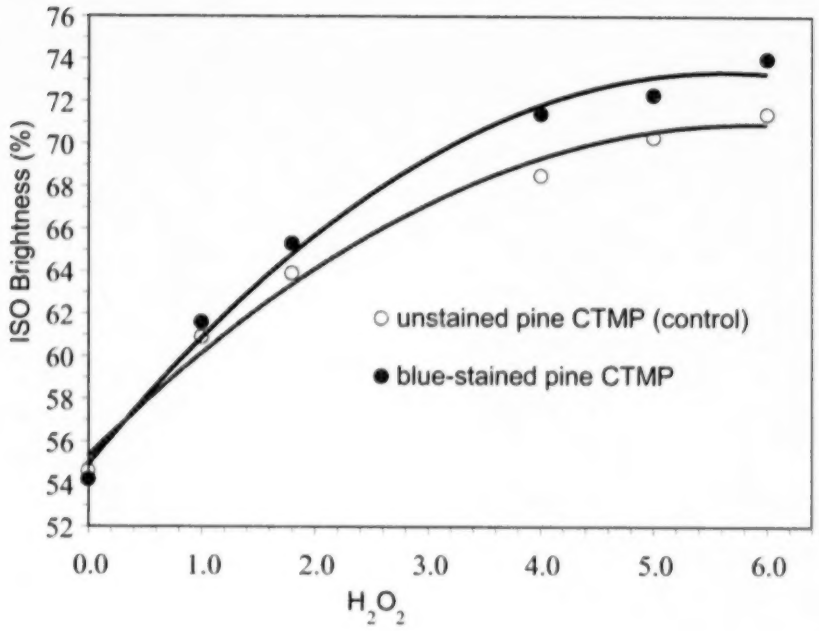


Figure 10a. Brightness of the unstained and blue-stained CTMP versus H_2O_2 charge; NaOH charge = H_2O_2 charge (*see* Material and Methods for charges of Na_2SiO_3 and $MgSO_4$).

The unbleached, blue-stained pine CTMP had a lower CIE b* value than the unbleached, unstained CTMP, even though its initial brightness was slightly lower than that of the unstained pulp (Table 7). This indicated that the unbleached, blue-stained pine CTMP contained the blue-stain. Plot of CIE b* vs. ISO brightness of the peroxide-bleached, unstained and blue-stained pulps showed that the difference in the CIE b* between the two pulps became progressly smaller as the charge of peroxide used for the bleaching, and consequently the bleached brightness, was increased (Figure 10b: CIE b* versus ISO brightness of the unstained and the blue-stained pine CTMP during alkaline hydrogen peroxide bleaching). This suggested the increasing removal of the blue-stain from the blue-stained pulp. No significant difference in peroxide consumptions during the bleaching of the two CTMP pulps was found.

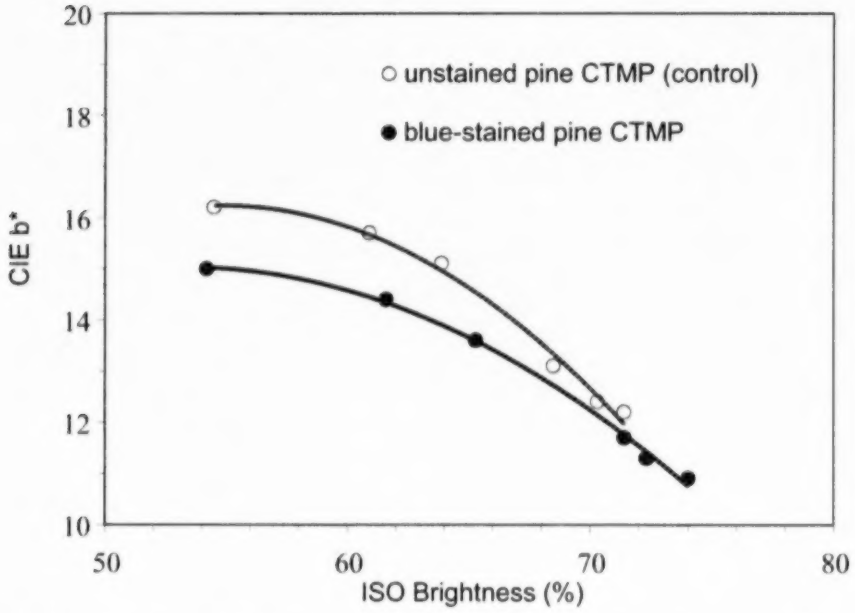


Figure 10b. CIE b* versus ISO brightness of the unstained and the blue-stained pine CTMP during alkaline hydrogen peroxide bleaching.

Similar to the blue-stained TMP, the blue-stained CTMP did not respond to sodium hydrosulfite bleaching as well as the unstained pulp, but the hydrosufite-bleached, blue-stained pulp again had a lower CIE b* than the bleached, unstained pulp (Table 7).

Table 7. ISO brightness and CIE b* of the sound and the blue-stained pine CTMP bleached with various amounts of H_2O_2 and NaOH (see Material and Methods for charges of Na_2SiO_3 and $MgSO_4$), or with $Na_2S_2O_4$

H_2O_2 / NaOH (% OD pulp)	$Na_2S_2O_4$ (% OD pulp)	Sound CTMP		Blue-stained CTMP	
		ISO Brightness (%)	CIE b*	ISO Brightness (%)	CIE b*
- / -	- / -	54.5[a]	16.2[a]	54.2[a]	15.0[a]
1.0 / 1.0		60.9	15.7	61.6	14.4
1.8 / 1.8		63.9	15.1	65.3	13.6
4.0 / 4.0		68.5	13.1	71.4	11.7
5.0 / 5.0		70.3	12.4	72.3	11.3
6.0 / 6.0		71.4	12.2	74.0	10.9
	1.0	61.8	14.4	61.0	13.0
	2.0	62.5	13.7	60.9	12.5

[a]value for unbleached pulp.

Further studies on the peroxide bleaching of the CTMP pulps showed that caustic (4%.0 – 6.0% OD pulp charge) had a very small effect on the bleach response of the pulps, and that for a given peroxide charge, the bleached brightness of the blue-stained CTMP was always higher than that of the control, unstained CTMP (Figure 11: Effect of NaOH on the alkaline hydrogen peroxide bleaching of the unstained and the blue-stained CTMP).

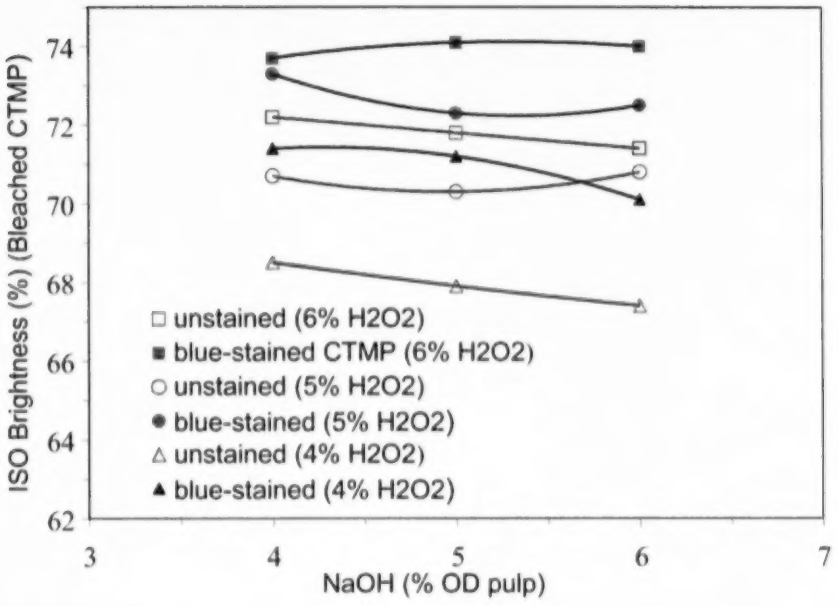


Figure 11. Effect of NaOH on the alkaline hydrogen peroxide bleaching of the unstained and the blue-stained CTMP; Na_2SiO_3 = 3.0% (OD pulp) and $MgSO_4$ = 0.05% (OD pulp).

Light-Induced Yellowing of the Peroxide-bleached, Unstained and Blue-stained Pine TMP or CTMP

The light-stability of the peroxide-bleached, blue-stained pine TMP was identical to that of the peroxide-bleached, unstained pine TMP (Figure 12: ISO brightness of the peroxide-bleached, unstained and blue-stained pine TMP or CTMP versus ambient light exposure time.). Interestingly, the light-stability of the peroxide-bleached, blue-stained pine CTMP was slightly higher than that of the unstained pine CTMP bleached to the same initial brightness value (Figure 12).

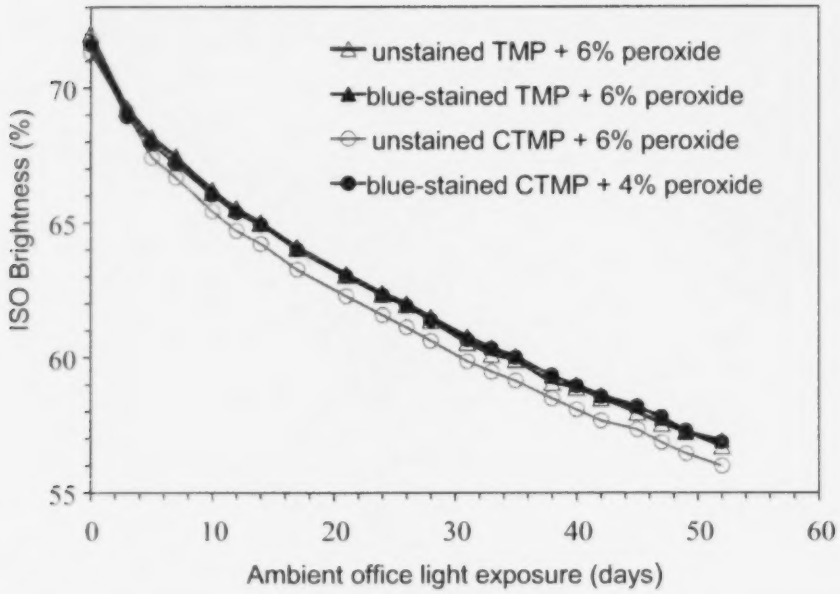


Figure 12. ISO brightness of the peroxide-bleached, unstained and blue-stained pine TMP or CTMP versus ambient light exposure time.

Conclusions

- Blue-stained sample had increase in fine and pin chip contents than that of sound sample.
- There was no significant amount of decay in blue-stained chips.
- There was a slight decrease in chip density of blue-stained sample than that of sound sample.
- There was no well-defined relationship between refining energy, fibre properties, strength properties, or optical properties of mechanical pulps produced from blue-stained and sound lodgepole pine chips.
- Blue-stained pine TMP does not respond to sodium hydrosulfite bleaching as well as unstained pine TMP; but it responds to alkaline hydrogen peroxide bleaching as well as unstained pine TMP at high peroxide charges ($\geq$ 4.0% peroxide OD pulp);
- Blue-stained pine CTMP has a better response to alkaline hydrogen peroxide bleaching but a poorer response to sodium hydrosulfite bleaching than unstained pine CTMP;
- The hydrosulfite-bleached, blue-stained pine TMP or CTMP has the advantage of low yellowness (CIE b*) over the hydrosulfite-bleached, unstained pulp;
- The light-stability of the peroxide-bleached, blue-stained TMP is similar to that of the peroxide-bleached, unstained TMP, but the light-stability of the peroxide-bleached, blue-stained CTMP is slightly higher than that of the peroxide-bleached, unstained CTMP.

Implications

The results from this preliminary study indicate that blue-stained lodgepole pine chips can be used in both thermomechanical and chemithermomechanical pulping processes without any significant detrimental effects on refining energy, strength, or optical properties. Because of the limited sampling of this present study, an in-depth study is recommended with large number of samples where length of beetle-infestation, degree of blue-stain, and rate of deterioration after beetle attack are well-documented.

Acknowledgements
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Appendix A. Properties of Thermomechanical Pulps of Sound and Blue-Stained Lodgepole Pine

	TMP Sound				TMP Blue-Stained			
Unscreened CSF (mL)	76	106	168	253	79	113	159	241
Specific Energy (MJ/kg)	12.3	10.6	9.7	7.5	12.3	11.0	10.4	8.1
Screened CSF (mL)	87	121	175	292	80	115	165	261
Reject (% od pulp)	0.0	0.1	0.1	0.7	0.0	0.0	0.1	0.2
Apparent Sheet Density (kg/m^3)	353	315	294	253	359	318	312	268
Burst Index ($kPa \cdot m^2/g$)	2.2	1.8	1.8	1.4	2.2	2.1	2.0	1.7
Tensile Index ($N \cdot m/g$)	32.7	29.2	27.7	20.1	34.8	31.2	30.5	25.9
Stretch (%)	1.34	1.32	1.33	1.04	1.36	1.34	1.31	1.28
Tear Index ($mN \cdot m^2/g$) (4 Ply)	6.2	6.6	7.2	6.9	6.5	7.2	8.5	8.9
Brightness (%)	54	55	54	53	55	56	54	54
ISO Opacity (%)	97.2	96.3	95.7	94.5	97.0	96.4	96.0	95.1
Scattering Coeff. (cm^2/g)	627	616	570	524	602	587	550	526
Sheffield Roughness (SU)	195	249	280	344	206	240	248	329
R - 48 Fraction (%)	52.2	53.3	58.6	62.9	52.1	55.2	61.3	64.5
Fines (P-200) (%)	25.7	24.8	23.9	20.7	26.7	25.2	23.6	21.3
W. Weighted Average Fibre Length (mm)	1.76	1.80	2.01	2.05	1.95	2.04	2.22	2.31
L. Weighted Average Fibre Length (mm)	1.28	1.30	1.49	1.53	1.38	1.47	1.66	1.72
Arithmetic Average Fibre Length (mm)	0.68	0.69	0.78	0.80	0.67	0.71	0.79	0.82

Appendix B. Properties of Chemothermomechanical Pulps of Sound and Blue-Stained Lodgepole Pine

	CTMP Sound			CTMP Blue-Stained		
Unscreened CSF (mL)	104	155	203	99	154	216
Specific Energy (MJ/kg)	13.3	11.2	9.6	12.4	10.6	9.1
Screened CSF (mL)	105	157	216	109	152	208
Reject (% od pulp)	0.0	0.0	0.0	0.0	0.0	0.0
Apparent Sheet Density (kg/m^3)	375	344	321	380	352	323
Burst Index ($kPa \cdot m^2/g$)	2.6	2.3	2.1	2.4	2.1	1.9
Tensile Index ($N \cdot m/g$)	39.1	35.1	31.8	37.6	32.9	31.0
Stretch (%)	1.37	1.35	1.28	1.28	1.13	1.22
Tear Index ($mN \cdot m^2/g$) (4 Ply)	7.0	7.6	8.1	6.8	7.0	7.7
Brightness (%)	54	55	55	55	56	55
ISO Opacity (%)	95.3	94.4	93.6	95.3	94.2	93.4
Scattering Coeff. (cm^2/g)	521	508	488	508	488	464
Sheffield Roughness (SU)	165	217	258	156	197	251
R - 48 Fraction (%)	55.1	57.0	59.3	51.2	52.6	54.6
Fines (P-200) (%)	22.8	22.3	20.4	22.9	22.2	20.9
W. Weighted Average Fibre Length (mm)	1.88	1.95	2.03	1.88	1.94	1.94
L. Weighted Average Fibre Length (mm)	1.38	1.45	1.50	1.31	1.35	1.36
Arithmetic Average Fibre Length (mm)	0.70	0.75	0.79	0.64	0.66	0.67

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